INVESTIGATION ON CYCLIC DEFORMATION BEHAVIOUR OF REINFORCED STEEL BARS

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ABSTRACT

In this study, cyclic deformation behaviours of 8-mm diameter reinforced steel bars produced by the hot rolling and the tempcore processes, whose carbon equivalent values were 0.52% and 0.41% respectively, were compared. The microstructure of the hot rolled bar was composed of ferrite and pearlite with a homogenous hardness distribution throughout the cross-section. On the other hand, the tempcored bar exhibited a microstructure consisting of tempered martensite in the outer sections and ferrite/pearlite in the center. This microstructure was accompanied with a hardness profile where the hardness decreased as the distance from the surface increased. In spite of its low carbon equivalent value, the tempcored bar exhibited higher yield strength than the hot rolled bar. However, low cycle fatigue tests conducted under the frequency of 1 Hz. in sinusoidal wave form revealed that, above the critical strain amplitude of 0.33%, the tempcored bars exhibited shorter fatigue life than the hot rolled bars. At the strain amplitude values lower than 0.33%, fatigue life of the tempcored bars was superior when compared to the hot rolled bars.

1 INTRODUCTION

Due to the technological improvements in the recent years, reinforced steel bars are used in increasing amounts in building industry. Improved mechanical properties as well as good weldability are the main features expected from reinforced steel bars. When compared to conventional hot rolled steel bars, the tempcored bars satisfactorily meet these requirements. High performance of the tempcored steel bars can be attributed to their unique microstructures. It is well known that martensite is formed in the outer sections of the bars during the tempcore process due to the rapid cooling and then tempered by the heat of the hot core [1].

In the literature, there are many data comparing the static strength of hot rolled and the tempcored steel bars. To our knowledge, the dynamic behaviour of these steels was compared in limited publications [2]. Since steel bars used in a building are subjected to periodical loading, which accompanies by heavy deformation during an earthquake, dynamic response of reinforced steel bars has a critical importance beside static strength. In this study, we aimed to compare cyclic behaviours of the reinforced steel bars produced by the hot rolling and the tempcore process.

2 EXPERIMENTAL DETAILS

Reinforced steel bars of 8-mm diameter used in this investigation had been produced by the hot rolling (HR) and the tempcore (TC) processes. The chemical compositions and corresponding carbon equivalent ($C_{eq.}$) values of the bars are given in Table 1.

Table 1: The chemical compositions of the investigated steels.

Bar	% C	% Mn	% Si	% P	% S	%$C_{eq.}$
HR	0.38	0.89	0.20	0.016	0.038	0.52
TC	0.16	1.13	0.13	0.038	0.054	0.41

Characterization of the reinforced steel bars was made by microscopic examinations, hardness measurements and tensile tests. Cross sections of the bars were prepared metallographically in the standard manner and etched with 2% Nital. Hardness measurements were conducted on a microhardness tester with a Vickers indenter under an indentation load of 200 g. Tensile tests were made at a cross head speed of 5 mm/min for the samples having a free length of 90 mm between the grips.

Fatigue behaviour of the reinforced steel bars was studied under low cycle fatigue (LCF) test conditions with a Dartec servohydraulic testing machine. The free length of the bars between grips was 90 mm. During LCF tests, the bars were periodically strained at 1 Hz in sinusoidal wave form. Strain and number of cycles to failure were continuously recorded. Total strain was selected as the control parameter and the failure criteria was complete fracture of the samples.

3 RESULTS AND DISCUSSIONS

Microscopic examinations conducted on the cross sections of the bars revealed that the microstructure of the hot rolled bar is uniform and consisted of ferrite and pearlite. The tempcored bar exhibited completely different microstructures at the outer section and at the core. The outer section contained tempered martensite, while the core was composed of ferrite and pearlite. The results of the hardness measurements presented in Fig. 1 are in good agreement with the microscopic examinations. The hot rolled bar yielded almost the same hardness values throughout the cross section due to its homogenous microstructure. On the cross section of the tempcored bars, high hardness values were obtained from the outer sections of the bars, which have tempered martensite microstructure. Thus, the tempcore process resulted in 20% higher hardness at the surface than at the core. When compared to that of the hot rolled bar, the core of the tempcored bar, where a ferrite/pearlite microstructure was present, exhibited lower hardness due to its low $C_{eq.}$ value (Table 1). The results of the tensile tests are listed in Table 2 revealed that, the tempcored bar exhibited higher yield strength than the hot rolled bar due to the presence of tempered martensite at its outer surface.

100 µm

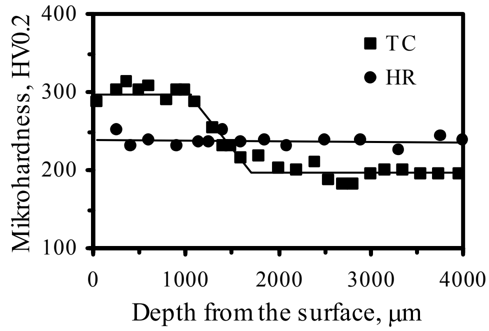

Figure 1: Hardness distribution throughout the cross section of the samples.

Table 2: The results of the tensile tests.

Sample	Yield strength, MPa	Tensile strength, MPa	Elongation at fracture, %
HR	488	731	19.9
TC	574	639	16.6

Fig. 2 shows "Total strain amplitude ($\Delta\varepsilon_t/2$) vs. Number of cycles to failure (N_f)" curves of the investigated bars. The arrow in Fig. 2 represents the data corresponding to the total strain amplitude at which the bars remain uncracked beyond 10^4 cycles. The following emprical equations can be drawn to analyse the LCF behaviour of the examined bars for the hot rolled and the tempcored bars, respectively:

$$\frac{\Delta\varepsilon_t}{2} = 0.020\,(N_f)^{-0.26} \qquad (1)$$

$$\frac{\Delta\varepsilon_t}{2} = 0.014\,(N_f)^{-0.20} \qquad (2)$$

where, $\Delta\varepsilon_t/2$, is the total strain amplitude and (N_f) is the number of cycles to failure.

Since the $\Delta\varepsilon_t/2$ vs. N_f curves of the hot rolled and the tempcored bars intersect with each other as seen in Fig. 2, the exact value of the critical intersecting point can be calculated as 1350 cycles by utilizing eqns. (1) and (2). This critical cycle to failure corresponds to a critical total strain amplitude ($\Delta\varepsilon_{tc}/2$) of 0.33%. Based on this critical total strain amplitude value and the trend of the curves plotted in Fig. 2, it can be stated that hot rolled bars exhibited longer fatigue life than the tempcored bars at the total strain amplitudes higher than 0.33 %. Below this critical value, the tempcored bars require more cycles than the hot rolled bars to be failed.

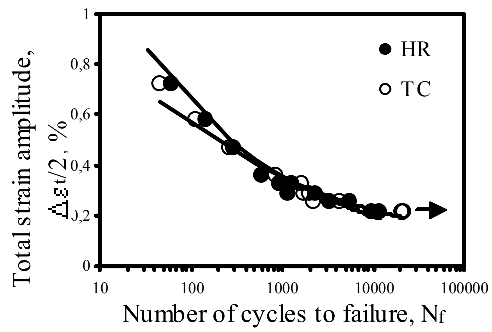

Figure 2: Total strain amplitude ($\Delta\varepsilon_t/2$) vs. Number of cycles to failure (N_f) curves.

"Strain amplitude ($\Delta\varepsilon/2$) vs. strain reversals ($2N_f$)" graphs, in which the the elastic and the plastic components of the total strain amplitude were presented, were plotted in logarithmic scale for the examined bars to analyse the LCF data (Fig. 3). Details of this process were given elsewhere [3]. For both bars, the plastic component is higher than the elastic component at relatively high strain amplitudes, while the opposite is valid at low strain amplitudes. The elastic and the plastic components of the total strain amplitude as afunction of the strain reversals can be expressed as;

$$\frac{\Delta\varepsilon_t}{2} = 0.023\ (2N_f)^{-0.04} + 0.032\ (2N_f)^{-0.39} \qquad (3)$$

$$\frac{\Delta\varepsilon_t}{2} = 0.024\ (2N_f)^{-0.04} + 0.028\ (2N_f)^{-0.38} \qquad (4)$$

for the hot rolled and temcored bars, respectively. Where, $\Delta\varepsilon_t/2$ is the total strain amplitude and $2N_f$ is the strain reversals.

Fig. 3 depicts that the elastic and the plastic components of the total strain amplitude are equal to each other at a critical strain reversal. This critical intersecting point of strain reversal is known as "fatigue life transition ($2N_t$)". N_t values of the hot rolled and the tempcored bars were found as 951 and 828 cycles, respectively. Since high N_t value indicates that the plastic component of the total strain amplitude is dominant than elastic component during fatigue tests [4,5], it can be concluded that the hot rolled bars expanded most of their fatigue life at plastic deformation region when compared to the tempcored bars. Thus, the hot rolled bars exhibited plasticity dominated failure whereas the tempcored bars yielded strength dominated failure.

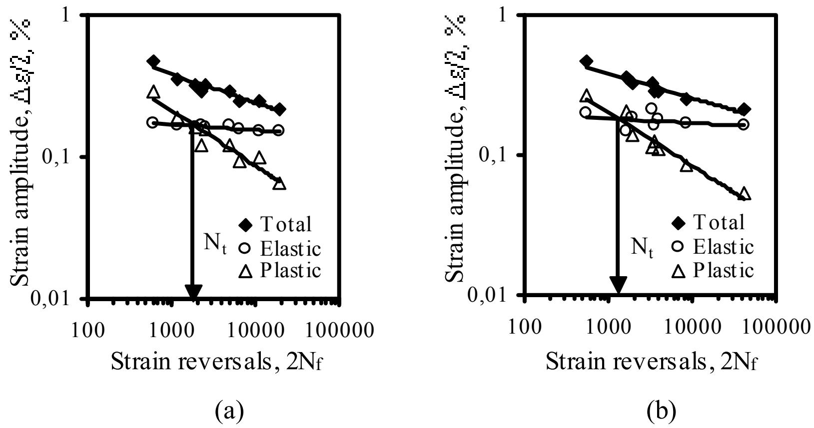

Figure 3: Elastic and plastic components of the total strain vs. strain reversals for (a) the hot rolled and (b) the tempcored bars.

Further analysis of the fatigue tests were made by plotting "Monotonic and Cyclic stress-strain" diagrams as depicted in Fig. 4. The monotonic stress-strain curves were obtained from tensile tests, while the cyclic stress-strain curves were plotted by utilising steady state stress values for each total strain amplitude, according to the Ramberg-Osgood relationship [6]. Since the monotonic stress-strain curves lie above the cyclic stress-strain curves in Fig. 4, it is clear that both bars were subjected to cyclic softening during the LCF tests.

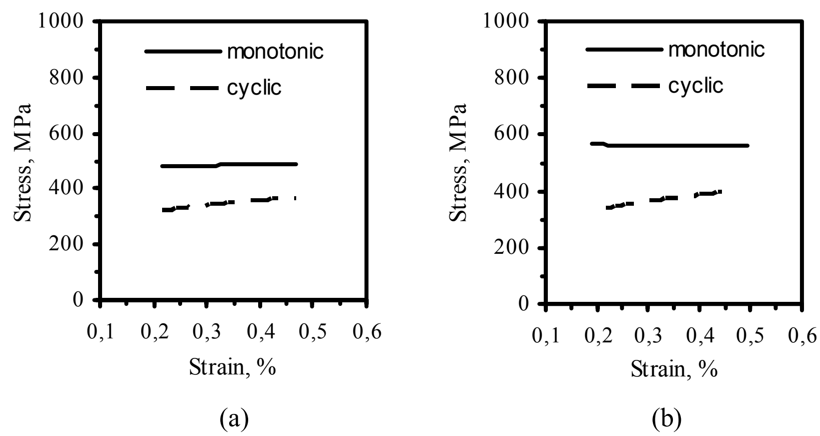

Figure 4: Monotonic and cyclic stress-strain curves for (a) the hot rolled and (b) the tempcored bars.

4 CONCLUSIONS

The following conclusions can be drawn according to the results of the present study conducted on 8 mm hot rolled and the tempcored reinforced steel bars, whose carbon equivalent values were 0.52 and 0.41 %, respectively:

1. At total strain amplitudes higher than 0.33% the hot rolled bars yielded longer fatigue life than the tempcored bars. However, opposite observation is valid for the total strain amplitudes lower than 0.33 %.
2. When compared to the tempcored bar, the hot rolled bar expanded most of its fatigue life in the plastic deformation region, according to the fatigue life transition approach. Both bars exhibited cyclic softening during cyclic testing.

5 REFERENCES

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